Renewable and Sustainable Energy Reviews 30 (2014) 555–564

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Environmental efficiency of investments in renewable energy: Comparative analysis at macroeconomic level

Claudiu Cicea *, Corina Marinescu, Ion Popa, Cosmin Dobrin

The Bucharest University of Economic Studies, Piata Romana, No. 6, Bucharest, Romania

ARTICLE INFO

Article history:
Received 12 January 2013
Received in revised form
17 October 2013
Accepted 22 October 2013
Available online 16 November 2013

Keywords:
Efficiency indicators
Environmental efficiency
Investment
Kaya identity
Renewable energy

ABSTRACT

This paper aims to bring into attention the concept of renewable energy investments' efficiency and to study one of the three concepts related to it, namely environmental efficiency of investments in renewable energy. The analysis is undertaken at macroeconomic level for several countries in Europe; some of them are member states of European Union and were observed over the period between 1990 and 2008. The method assumes the study of the econometric models based on Kaya identity, an equation widely used in studies regarding emissions, trends and future emissions scenarios. Working with time series and cross-sectional data, a panel data approach is needed. Indicators like energy intensity, CO_2 intensity and gross domestic product per capita and per unit of investment are used, as they establish a connection between effects and efforts (a prerequisite for studying the efficiency). A novelty of this research lies in the calculation of environmental efficiency index after an original method proposed by authors. The findings of this analysis reveal that there are both countries with high and low environmental efficiency of investments in renewable energy.

Contents

1. Introduction

The beginning of new millennium was marked by a series of developments that will surely be amplified in coming years. In the same time they will generate reactions triggered by the desire of permanently change in the human society lifestyle. In terms of more limited resources and of needs constantly multiplying and diversifying, the concept of efficiency has a permanently valability in actual economic and social life. Currently, any human activity (economic or social) is initiated considering the principles of efficiency and effectiveness. In a general sense, efficiency represents the interaction established between the volume and structure of undertaken efforts and the volume and structure of obtained results. Continuous improvement of individual living standards and the economic development of the community should be always based on a prior study of human activity's efficiency. Strongly connected with the study of economic efficiency, there is an another important concept, namely the investment's efficiency. The investments highly stimulate any development process and they are considered "as a material support for economic growth" [1].

As we stated before, the limited resources represent one of the main reasons for a moderate consumption; this moderation should keep the satisfying of individual necessities and should not affect the environment or the social well-being. As we considered in a previous work, energy consumption fits perfectly for discussing aspects like economic, social and environmental aspects of development. In the

* Corresponding author: Tel.: +40 722 624 927.
E-mail address: claudiu.cicea@man.ase.ro (C. Cicea).

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http://dx.doi.org/10.1016/j.rser.2013.10.034

same time, we should not forget that energy field is the most debated issue in the last decades, due to the global context of sustainable development. Specialists are focused on renewable energies and on their promotion, considering the benefits they bring and the advantages they have against traditional energy. One of the many ways of convincing the humanity on the green energy's importance for our future, is to study the efficiency of investments allocated to this type of energy.

It is well known that the investments in renewable energy (RE) registered an increasing trend in the last decade all around the world [2]. Studying their efficiency provides insights for further developing of new investments. The topic of investments' efficiency is very complex, based on a large number of effects generated by those investments. As shown in a prior work [3], these effects generate three distinctive concepts:

- Economic efficiency of investments;
- Environmental (or ecological) efficiency of investments;
- Social efficiency of investments.

All three concepts will be treated in separate works. In the present paper, we will focus on studying the environmental efficiency of investments in renewable energy. The proposed investigation will be conducted at macroeconomic level (the society as a whole) using energy and economic indicators for several states from Europe, some of them part of European Union: CO_2 emissions from electricity and heat production, total (million metric tons); GDP per capita (constant 2000 dollars); electricity production (kWh); electricity production from renewable sources (kWh); gross inland consumption of energy (all products) (1000 tones oil equivalent). As far as we are concerned, there is no study at macroeconomic level for environmental efficiency of renewable energy investments. The method we are proposing is different from the classic (which asses the economic efficiency based on several specific indicators). Moreover, it follows an econometric approach, in order to build a linear regression model for revealing the efficiency of investments. Such an analysis reveals comparisons among countries and each country's position as against European Union's situation (here, European Union has 22 countries).

2. Literature review

Efficiency is a very complex topic. It should be analyzed from an economic and a social point of view, at macroeconomic and microeconomic level, static and dynamic, by branches of national economy, etc. An efficiency analysis provides guidance for projects in areas with priority for the national economy, projects that contribute to the achievement of sustainable development objectives [4]. The rapidly and unpredictable changes in the economic and social aspects of the economy (sometimes called new economy, digital economy, knowledge-based economy [5,6]), require complex approaches on investment decisions [7].

The environmental efficiency is a relatively new concept, born from the concerns about global warming, CO_2 emissions mitigation, resource recycling and other environmental factors [8–10]. Researches on environmental efficiency evaluation highlight the "urgent need" [11–14] for developing new methods and applications for efficiency assessment. Some use the Data Envelopment Analysis (DEA) method [15], others use estimation procedures of traditional distance functions that facilitate the deployment of environmental efficiency and productivity studies within a parametric stochastic context [16]. A methodological difficulty was afterwards associated to the first type of method [17]. The difficulty lies in unifying operational performance on desirable outputs with environmental performance on undesirable outputs. Therefore, economic and mathematical perspectives of environmental assessment were approached.

Another interesting perspective of assessing the environmental efficiency is the one of the Rodríguez Morilla et al. [18] who uses the Social Accounting Matrix and Environmental Accounts (SAMEA) for Spain, in order to determine the so-called multipliers for environmental efficiency evaluation.

The environmental efficiency is also found in the literature as ecological efficiency or eco-efficiency. In their research, Reith and Guidry [19] analyze the eco-efficiency in the agricultural sector; in the same area, Gómez-Limón et al. [20] study the eco-efficiency of the olive farms from Andalusia (in their study, they bring into light concepts like eco-efficiency management and eco-efficiency production). Michelsen et al. [21] present a methodology for understanding and measuring eco-efficiency in the furniture production, referring to extended supply chains. Li et al. [22] undertake an analysis at city level for determining the eco-efficiency of a residential development by proposing a new methodology with implications for policy-makers and decision-makers in the industry. In their work, Côté et al. [23] discuss different definitions for eco-efficiency, comparing several businesses and pointing out the driving forces of eco-efficiency. Fernández-Viñé et al. [24] perform their research in the small and medium sized enterprises from Venezuela in the context of eco-efficiency, revealing in the end differences among them. Taking into consideration the examples provided above, we appreciate that "environmental efficiency" is commonly used when conducting macroeconomic analysis; the "eco-efficiency" term is more used when conducting microeconomic analysis.

Moreover, the concept of ecological efficiency also seems to reflect facts happening at microeconomic level [25,26]. Slobodkin [27] appreciates that ecological efficiency represents "the fraction passed on to the next higher trophic level of energy consumed by a particular ecological unit – for example, a population or trophic level". He manages to measure this type of efficiency on a scale from 0 to 1, considering that "statements about ecological efficiency of entire communities are meaningless". There are also other authors who tried to evaluate the ecological efficiency, this time for a cogeneration system in a hospital [28]. Their findings revealed that the method can be applied to any sort of thermal system.

The environmental efficiency has been studied as a sole element of interest or in relation with other important aspects regarding efficiency. For instance, there are works which analyze the link between environmental and productive efficiency for EU members and states from US. The connection between the environmental efficiency and social well-being was transposed in a new indicator called Happy Planet Index (HPI) [29]. It establishes the environmental efficiency level that supports the well-being of people in a country. In addition to this, Knight and Rosa [30] constructed a measure for environmental efficiency of well-being (EWEB), using the ecological footprint per capita and average life satisfaction. Their findings reveal that countries widely vary in the efficiency and that the effect of economic development on EWEB is a negative one, as well as the one of income inequality; just the social capital has a positive impact on environmental efficiency.

Furthermore, the environmental efficiency was subject to studies all around the world; for instance, Zaim and Taskin [31] focused on OECD countries using non-parametric techniques. A year later, Zofío and Prieto [32] applied the Data Envelopment Analysis to calculate desirable output losses when specific environmental standards on undesirable production are set by the authorities. The same method is applied by Jaraitė and Di Maria [33] who measure environmental efficiency and productivity of the European Union's public power generation. Another scientific research is conducted for United States by Welch and

Barnum [34] who briefly conclude that "some plants that are currently less efficient than those on the production frontier could produce the same amount of electricity with less carbon output and less fuel input. Additionally, many plants on the production frontier could improve both cost and carbon efficiency by changing their mixture of fossil-fuel inputs".

In order to analyze the environmental efficiency in the field of energy, the authors felt the need to use several specific indicators that could facilitate their research. The most used indicators in such studies are: carbon intensity [35], energy intensity [36], CO_2 emissions [37,38], energy consumption [39,40], and energy production [41,42]. The energy intensity is considered a "measure of the amount of energy it takes to produce a dollar's worth of economic output, or conversely the amount of economic output that can be generated by one standardized unit of energy" [43]. The Carbon intensity is "the amount of carbon (in terms of weight) emitted per unit of energy consumed. A common measure of carbon intensity is the weight of carbon per British thermal unit (BTU)" [44].

In a certain way, these two indicators reflect efficiency, as they talk about the efforts made to obtained some effects (the case of energy intensity) or about the effects obtained with some efforts (the case of carbon intensity). The other three mentioned indicators reflect the absolute dimension of several aspects, being called volume indicators.

There is a simple equation that links together the emissions, wealth, energy intensity and population, named Kaya identity after the Japanese researcher Yoichi Kaya [45]. As Rogner et al. [46] define it, the equation is "a decomposition that expresses the level of energy related CO_2 emissions as the product of four indicators:

a carbon intensity (CO_2 emissions per unit of total primary energy supply (TPES));
b energy intensity (TPES per unit of GDP);
c gross domestic product per capita (GDP/capita);
d population".

Based on Kaya identity, Archer [47] from University of Chicago developed a calculator to help projecting future carbon emissions; anyone can use this online calculator [48] or "Kaya identity Scenario Prognosticator" as it is called. In order to generate the model's output, one can vary the four input terms: "population, GDP per capita, energy consumed per unit of GDP (energy intensity), and carbon emissions per unit of energy consumed (carbon efficiency)" [49]. The online calculator produces output plots useful for exploring implications of each variable on resulted emissions or for comparing with the observed trends up to 2000.

Raupach, Marland, Ciais, Le Quere, Canadell, Klepper and Field [48] use the following form of Kaya identity:

$$F = P \times \frac{G}{P} \times \frac{E}{G} \times \frac{F}{E} = Pgef \tag{1}$$

where F represents the global CO_2 emission flux from fossil fuel combustion and industrial processes, P is the population, G is world GDP or gross world product, E represents the global primary energy consumption, G/P represents the per-capita world GDP, further noted with g; E/G is the energy intensity of world GDP, further denoted with e; F/E represents the carbon intensity of energy, further denoted with f.

They consider that the world can be divided into several regions and for each of them, a Kaya identity can be written; the authors reveal their findings [50]: "the developed regions contributed most to cumulative emissions and least to emissions growth, and vice versa for developing regions" and "developed nations have used two centuries of fossil-fuel emissions to achieve their present economic status, whereas developing nations are currently experiencing intensive development with a high energy requirement, much of the demand being met by fossil fuels".

Caiazza [51] uses the Kaya identity to analyze decarbonization of the economy. He starts from the classic formula of Kaya identity, written as follows:

$$C = P \times \frac{\mathrm{GDP}}{P} \times \frac{\mathrm{TE}}{\mathrm{GDP}} \times \frac{C}{\mathrm{TE}} \tag{2}$$

In this formula, C represents carbon emissions, P represents population, TE represents the energy consumption, (TE/GDP) stands for energy intensity, (C/TE)stands for carbon intensity. The author groups the factors, obtaining: $P \times (\mathrm{GDP}/P) = \mathrm{GDP}$ and $(\mathrm{TE/GDP}) \times (C/\mathrm{TE}) = $technology. So emissions=GDP × technology. Further emissions/GDP=technology. In this moment, one can appreciate that "decarbonization of the economy is reflected in a decrease in the ratio of carbon dioxide emissions to gross state product" [51]. By observing the proposed equation, the author realizes that there are four ways to decrease emissions:

1. Regarding population factor, less people could generate less emission.
2. Regarding GDP per capita, a smaller economy and a limitation of wealth could also mitigate emissions.
3. Regarding energy intensity, the author appreciates that people should do the same or more with less energy.
4. Regarding carbon intensity, by combining or replacing energy sources, energy can be generated with fewer emissions.

Only two of these possible transformations are feasible: the ones regarding energy intensity and carbon intensity. The author projects all four factors, in order to combine projections and calculate decarbonization. It results an annual average decarbonization rate ranging from 2.1% to 3.2%, so it could meet the Climate Action Plan goals of 2030.

Going further, an interesting application of an extended Kaya identity reveals the importance of renewable energy in carbon emissions mitigation. We refer to the work of Zhang and Ang [52] who define the following relation:

$$C = \sum C_i = \sum (E_i/E)(C_i/E_i)(E/Y)(Y/P)P = \sum S_i F_i IGP \tag{3}$$

In this equation, the notations are as follows: i, fuel type; E, total energy consumption of all fuel types; E_i, energy consumption of fuel type i; C, total CO_2 emissions from all fuel types; C_i, CO_2 emissions from fuel type i; Y, GDP; P, population; S, the consumption share of fuel type i; F, the CO_2 emission coefficient for fuel type i; I, the aggregate energy intensity; G, the GDP per capita or income.

The authors used the decomposition method in order to observe changes in emissions associated to factors specified in the equation. So, as authors indicate, "the decomposed components of a change in C that are associated with these factors are, respectively, referred to as fuel share effect ΔC_{fsh}, emission coefficient effect ΔC_{emc}, intensity effect ΔC_{int}, income effect ΔC_{ypc}, and population effect ΔC_{pop}". As the analysis is undertaken for three world regions, the difference in emission level between two regions is:

$$\begin{aligned}\Delta C = C_1 - C_2 &= \sum S_{i1} F_{i1} I_1 G_1 P_1 - \sum S_{i2} F_{i2} I_2 G_2 P_2 \\ &= \Delta C_{fsh} + \Delta C_{emc} + \Delta C_{\mathrm{int}} + \Delta C_{ypc} + \Delta C_{pop} + \Delta C_{rsd}\end{aligned} \tag{4}$$

In this formula, a new term appears, namely ΔC_{rsd}, representing residuals. Four decomposition methods were applied in order to estimate each component's effect on emissions. It resulted that regardless the region, "income effect GDP (per capita) and population effect are generally the dominant forces leading to different emission levels"; the fuel share effect is minimal (the study

included the next sources for energy consumption: solids, oil, gas, nuclear, hydro and geothermal).

A similar approach is the one of Jung et al. [53] who calculate the total change in carbon emissions as “the sum of changes in production (ΔC_{pdn}), energy intensity (ΔC_{int}), fuel mix (ΔC_{mix}), emissions (ΔC_{emf}) and population (ΔC_{pop})”:

$$\Delta C_{tot} = C^T - C^0 = \Delta C_{pop} + \Delta C_{pdn} + \Delta C_{\text{int}} + \Delta C_{mix} + \Delta C_{emf} \tag{5}$$

The analysis covers five regions from South Korea, for which the next issues can be mentioned: on one hand the principal factor that influences CO_2 emissions' diminution is energy intensity; on the other hand, production effect maintains high levels of emissions and energy consumption.

Inspired by the previous extension of Kaya identity, O'Mahony [54] transformed the relation proposed by Zhang and Ang in the following formula:

$$C_{tot} = C_t - C_0 = C_{emc} C_{ffse} C_{repe} C_{\text{int}} C_{ypc} C_{pop} \tag{6}$$

In this new relation, C_{ffse} represents fossil fuel substitution effect and C_{repe} represents the renewable energy penetration effect, while C_{tot} is the index of annual change in total CO_2 emissions. The renewable energy component refers to hydro, wind, biomass, bio fuel, solar, geothermal and all factors are studied from 1990 to 2010 for Ireland. Among results of investigation, an important contribution to the drop in carbon emissions is brought by two factors: fossil fuel substitution effect and renewable energy penetration effect. The author concludes that in order to reach targets, policies should pursue the increase of renewables and the decrease of energy intensity.

Other analyses of these driving forces of carbon dioxide emissions with implication for policies are the ones of Duro and Padilla [55], Wang [56] and Pani and Mukhopadhyay [57]. Duro and Padilla have an interesting approach, conducting a comprehensive study on 114 countries and groups of countries: Temperate Zone, Eastern Europe, Tropical America, Tropical Africa, Southwest Asia, South-central Asia, and Southeast Asia. As a conclusion of their work, “international inequalities in per capita CO_2 emissions are mainly explained by inequalities in affluence—measured by per capita income—across countries” [55].

Wang focuses on China and United States, revealing that “output growth is a major source for increases in carbon dioxide emissions while decline in energy intensity is the main contributor to the reduction of emissions” [56]. Pani and Mukhopadhyay concentrate on 10 largest emitters: China, USA, Russia, India, Japan, Germany, Canada, UK, South Korea and Iran. Their analysis shows that “growth in population and income level are the major driving forces of emission, with the income effect being stronger than the population effect and increasing over time. It is found that the effect of population is determined not simply by the number but by its affluence, while the income effect is not homogeneous across countries”[57]. By studying the major driving forces of emission, authors provide measures to control them, policy prescriptions and adjustments.

Taking into account all the above aspects, we appreciate that starting from Kaya identity, we can study the environmental efficiency of investments in renewable energy. Such study has never been made before, as in many cases, decision makers are interested more in the economic efficiency of investments. This type of efficiency represents a concept describing the relationship between resources (spent on performing an investment process) and results (obtained from the same process) [58,59].

3. Methods

Taking into account the need to identify a relation for the environmental efficiency of investment in green energy, we tried to develop a model in a panel data approach. We started from the Kaya identity presented in the previous section and used the following indicators: CO_2 emissions from electricity and heat production, total (million metric tons) [60], GDP per capita (constant 2000 US $) [61], electricity production (kWh) [62], electricity production from renewable sources (kWh) [63], gross inland consumption of energy (all products), and 1000 t of oil equivalent [64].

Combining these indicators, we developed the following model which includes: the environmental efficiency index (calculated as a ratio between CO_2 emissions from electricity and heat production and investments in renewable energy, denoted with C/I), the energy intensity (calculated as the ratio between the gross inland energy consumption and the GDP per capita, denoted with E/G), the CO_2 intensity (calculated as the ratio between CO_2 emissions from electricity and heat production and gross inland energy consumption, denoted with C/E), GDP per capita and per unit of renewable investment (calculated as ratio between GDP per capita and investments in renewable energy, denoted with G/I).

The indicator estimating the investments in renewable energy is calculated as the share of electricity production from renewable sources in electricity production, after the idea found at Scandurra [65]. It was necessary to find a way to quantify these investments, as they could not be found in data bases for so many countries and for a longer period of time. The evolution of investments in renewable energy between 1990 and 2008 indicate an alternating trend in the first part of the considered period and an increasing trend in the second part, for European Union with 22 countries. Most countries tend to follow this trend. Another way of explaining investments in renewable energy is the one of Romano and Scandurra: "the ratio between renewable generation and the differences between Total Net Electricity Generation and the Net Electricity Imports" [66].

All things considered, our model emphasizes the next relation:

$$\frac{C}{I} = \frac{G}{I} \times \frac{C}{E} \times \frac{E}{G} \tag{7}$$

We use as a method of estimating the coefficients for indicators in this equation, the Ordinary Least Squares method, with cross section specific coefficients (in order to find country specific coefficients), fixed cross section effects (an individual intercept for each country) and cross section weights as we assumed that there is cross-section heteroskedasticity. So, the regression equation for the econometric analysis is:

$$\text{Ef}_{it} = a_i + b_i \times \text{GI}_{it} + c_i \times \text{CE}_{it} + d_i \times \text{EG}_{it} + \varepsilon_{it} \tag{8}$$

Ef_{it} is the environmental efficiency of RE investments index, GI_{it} is the GDP per capita and per unit of renewable investment, CE_{it} is the CO_2 intensity, EG_{it} is the energy intensity, i is the number of cross-sections, t is the period of time, ε_{it} is the error term, a_i is the intercept which varies within each cross-sectional unit, b_i, c_i, d_i are the coefficients to be estimated of the independent variables.

All these indicators are observed over the period 1990–2008, for a set of countries from Europe and for the European Union with 22 countries. We have chosen to conduct our analysis only until 2008, as this is the first year of the global economic crisis. The effects of the crisis were transposed, among others, in massive layoffs, reductions in production and cessation of investments, with different aspects and levels of intensity from one country to another. So we decided to leave apart the influence of the crisis on the variables.

After explaining the construction of our model, we consider appropriate to emphasize some differences from the classical Kaya equation and the other previous presented models. We chose to transform the Kaya identity, so we could use it in our investigation. Following the idea proposed by Yoichi Kaya in his equation, we only eliminated the variable representing population (as we need indicators which establish a connection between effects to

efforts); we did not include other variables, so the content of the identity could remain untainted. However, the second component regarding population remained in the equation as we used the variable GDP per capita and per unit of investment. This represents a first difference between our model and the available models in the literature. Furthermore, maybe the most relevant difference refers to the use of Kaya identity, which in our study is to shape the environmental efficiency of investing in green energy. All other studies make use of it in order to investigate projections of carbon emissions. Another difference consists of transformations of the factors included in the equation. Many authors transform the factors into effects (for instance, fossil fuel substitution effect or renewable energy penetration effect) on emissions, by applying decomposition methods. We also made a transformation on the factors, by combining them in order to express efficiency (a ratio between efforts and effects or a ratio between effects and efforts).

Table 1 shows the values for the environmental efficiency index of investments in green energy for 2008, the values for its components and the growth indices for each of them.

In Table 1, countries were classified after the values of environmental efficiency index in 2008. The values for European Union with 22 countries were considered base of the comparison, as we calculated the growth indices for all three indicators. These growth indices help us to explain to what extent the improvement of environmental efficiency is due to CO_2 emissions reduction or due to increases of investments in renewable energy. For instance for Romania, the environmental efficiency's improvement, compared to European Union (EU-22), is due to decreased CO_2 emissions by 55% and due to an increase of 26% in the level of renewable energy investments. This means that there is a positive influence from both growth indices (in Table 1, index of CO_2 emissions from electricity and heat production and index of investments in renewable energy) on the environmental efficiency index.

Going further with the examples, for Poland case, the high value of the environmental efficiency index of 39.0615 is due to increased emissions with 58% compared to the level of EU-22 and due to reduced investments with 80% compared to the level of EU-22. This means that there is a negative influence from both indices (in Table 1, index of CO_2 emissions from electricity and heat production and index of investments in renewable energy) on the environmental efficiency index.

Observing the growth indices of CO_2 emissions and renewable energy investments, we can group the countries considered for our analysis after three possible situations:

- The group of countries for which both growth indices indicate values greater than 100% (the level of EU-22): Iceland (ice), Latvia (lva), Norway (nor), Sweden (swe), Slovenia (slv), Austria (aut), Portugal (prt), Finland (fin), Denmark (dnk), and Romania (rom). This is a situation for which both indices have a positive influence on the environmental efficiency index.
- The group of countries for which both growth indices indicate values smaller than 100% (the level of EU-22): United Kingdom (gbr), Poland (pol), Germany (deu), Italy (ita), Turkey (tur), and Spain (esp). This is a situation for which both indices have a negative influence for the environmental efficiency index.
- The group of countries for which one of the indices shows a greater value than 100% and the other one a smaller value than 100%: Luxembourg (lux), Lithuania (lit), Hungary (hun), Belgium (bel), Bulgaria (bgr), France (fra), Netherlands (nld), Greece (grc), and Czech Republic (cze). This is a situation for which one of the indices has a positive influence for the environmental efficiency index (transposed either in the decreases of emissions either in increases of investments) and the other one a negative influence (transposed either in the increases of emissions either in decreases of investments) on the same environmental efficiency index.

Table 1
Values of environmental efficiency index in 2008.
Source: Authors' calculation.

No.	Country	Value of environmental efficiency index	CO_2 emissions from electricity and heat production	Investments in renewable energy	Growth index of environmental efficiency (%)	Growth index of CO_2 emissions from electricity and heat production (%)	Growth index of investments in renewable energy (%)
1	Iceland	0.0001	0.01	99.988	3,322,029	700,514	474
2	Latvia	0.0334	2.04	60.903	9919	3434	289
3	Luxembourg	0.1021	1.06	10.382	3254	6609	49
4	Norway	0.1264	12.57	99.403	2627	557	471
5	Sweden	0.1929	10.48	54.309	1722	668	258
6	Slovenia	0.2379	6.25	26.270	1396	1121	125
7	Austria	0.3422	23.63	69.043	971	296	327
8	Portugal	0.6498	20.92	32.192	511	335	153
9	Finland	0.7519	27.01	35.920	442	259	170
10	Denmark	0.8727	24.24	27.774	381	289	132
11	Lithuania	1.1094	5.02	4.525	299	1395	21
12	Romania	1.7098	45.34	26.516	194	155	126
13	EU-22	3.3224	70.051	21.084	100	100	100
14	Hungary	3.3843	19.93	5.889	98	351	28
15	Bulgaria	4.7444	31.35	6.608	70	223	31
16	Belgium	5.3407	28.23	5.286	62	248	25
17	France	5.3598	69.65	12.995	62	101	62
18	Greece	5.4552	49.86	9.140	61	140	43
19	Spain	5.9746	119.65	20.026	56	59	95
20	Turkey	6.4878	112.55	17.348	51	62	82
21	Netherlands	7.6819	68.01	8.853	43	103	42
22	Italy	8.8685	164.52	18.551	37	43	88
23	Czech Republic	14.8254	66.51	4.486	22	105	21
24	Germany	25.3907	363.28	14.308	13	19	68
25	Poland	39.0615	166.79	4.270	9	42	20
26	United Kingdom	40.5162	227.36	5.612	8	31	27

The country code was specified for each country, in order to understand the reported regression equations.

4. Results

After applying Least Squares method, the econometric model for the first group of countries, for which both growth indices (growth indices of CO_2 emissions and renewable energy investments) indicate values greater than 100%, is composed of ten regression equations:

$$Ef\_AUT = 0.9113 - 1.534 + 0.00093 \times GI\_AUT + 373.3901 \times CE\_AUT + 0.2728 \times EG\_AUT \quad (9)$$

$$Ef\_DNK = -3.4349 - 1.534 + 0.00125 \times GI\_DNK + 5254.7526 \times CE\_DNK - 4.2516 \times EG\_DNK \quad (10)$$

$$Ef\_FIN = -0.596 - 1.534 + 0.0014 \times GI\_FIN + 1069.5903 \times CE\_FIN + 0.7578 \times EG\_FIN \quad (11)$$

$$Ef\_ICE = 1.5339 - 1.534 + 0.000000444 \times GI\_ICE + 28.6846 \times CE\_ICE + 0.000194 \times EG\_ICE \quad (12)$$

$$Ef\_LVA = 1.3983 - 1.534 + 0.000933 \times GI\_LVA + 186.7023 \times CE\_LVA - 0.00127 \times EG\_LVA \quad (13)$$

$$Ef\_NOR = 1.3207 - 1.534 + 0.0003 \times GI\_NOR + 247.3497 \times CE\_NOR + 0.1483 \times EG\_NOR \quad (14)$$

$$Ef\_PRT = 0.0931 - 1.534 + 0.0022 \times GI\_PRT + 753.476 \times CE\_PRT + 0.3157 \times EG\_PRT \quad (15)$$

$$Ef\_ROM = -3.2954 - 1.534 + 0.0348 \times GI\_ROM + 1689.8231 \times CE\_ROM + 0.1121 \times EG\_ROM \quad (16)$$

$$Ef\_SLV = 1.0762 - 1.534 + 0.0005 \times GI\_SLV + 246.0724 \times CE\_SLV + 0.3645 \times EG\_SLV \quad (17)$$

$$Ef\_SWE = 0.9927 - 1.534 + 0.0004 \times GI\_SWE + 1132.2858 \times CE\_SWE + 0.1378 \times EG\_SWE \quad (18)$$

The second group of countries included in the analysis was the one for which both growth indices indicate values smaller than 100%. For this group, the regression equations are:

$$Ef\_DEU = -64.6661 - 106.3439 + 0.0171 \times GI\_DEU + 104287.9346 \times CE\_DEU + 3.7947 \times EG\_DEU \quad (19)$$

$$Ef\_ESP = 95.7653 - 106.3439 + 0.0076 \times GI\_ESP + 5543.6523 \times CE\_ESP + 0.66101 \times EG\_ESP \quad (20)$$

$$Ef\_GBR = -99.4405 - 106.3439 + 0.0091 \times GI\_GBR + 117454.106 \times CE\_GBR + 9.7692 \times EG\_GBR \quad (21)$$

$$Ef\_ITA = 89.1769 - 106.3439 + 0.0081 \times GI\_ITA + 9593.5869 \times CE\_ITA + 0.9475 \times EG\_ITA \quad (22)$$

$$Ef\_POL = -125.515 - 106.3439 + 0.0288 \times GI\_POL + 87237.4396 \times CE\_POL + 4.5835 \times EG\_POL \quad (23)$$

$$Ef\_TUR = 104.6794 - 106.3439 + 0.0206 \times GI\_TUR + 2755.923 \times CE\_TUR - 0.07903 \times EG\_TUR \quad (24)$$

Moving forward to the third group of countries for which one of the indices shows a greater value than 100% and the other one a smaller value than 100%, we report the following results:

$$Ef\_BEL = -33.0001 - 24.2533 + 0.0012 \times GI\_BEL + 63176.0191 \times CE\_BEL + 10.5774 \times EG\_BEL \quad (25)$$

$$Ef\_BGR = 13.2736 - 24.2533 + 0.019 \times GI\_BGR + 3297.3218 \times CE\_BGR + 0.4759 \times EG\_BGR \quad (26)$$

$$Ef\_CZE = -14.3323 - 24.2533 + 0.0118 \times GI\_CZE + 11399.4782 \times CE\_CZE + 2.7324 \times EG\_CZE \quad (27)$$

$$Ef\_FRA = 15.1755 - 24.2533 + 0.00305 \times GI\_FRA + 17663.5632 \times CE\_FRA + 0.3823 \times EG\_FRA \quad (28)$$

$$Ef\_GRC = 14.2784 - 24.2533 + 0.0038 \times GI\_GRC + 2454.5207 \times CE\_GRC + 2.5135 \times EG\_GRC \quad (29)$$

$$Ef\_HUN = -23.5156 - 24.2533 + 0.0037 \times GI\_HUN + 36983.9039 \times CE\_HUN + 4.1267 \times EG\_HUN \quad (30)$$

$$Ef\_LIT = 15.0916 - 24.2533 + 0.0031 \times GI\_LIT + 7259.8445 \times CE\_LIT + 0.8781 \times EG\_LIT \quad (31)$$

$$Ef\_LUX = 24.0216 - 24.2533 + 0.0000238 \times GI\_LUX + 67.6979 \times CE\_LUX + 2.4325 \times EG\_LUX \quad (32)$$

$$Ef\_NLD = -10.9928 - 24.2533 + 0.00302 \times GI\_NLD + 12180.0118 \times CE\_NLD + 7.3819 \times EG\_NLD \quad (33)$$

For European Union with 22 states, the estimated coefficients of the regression equation are:

$$Ef\_EU = -7.2027 + 0.004422 \times GI\_EU + 0.7913 \times CE\_EU + 3659.1982 \times EG\_EU \quad (34)$$

The EViews software used to conduct the analysis, always returns once with the estimated coefficients the correlation coefficient, *F*-statistic and its associated probability. They are available for observation in Table 2.

5. Discussion

Because we used our own indicator (called environmental efficiency index) as a proxy for environmental efficiency, we consider appropriate to comment upon its evolution for several countries. It is necessary to indicate the level of efficiency that has been attained by each country. It is obvious that we are looking for small values of the indicator, which indicate a high level of the environmental efficiency of renewable energy investments. We specify once again that the index is calculated as a ratio between effects (the CO_2 emissions) and efforts (the investments), and therefore we can consider that this index is a truly efficiency indicator. Here, the effects need to be minimized for certain efforts; in most cases, an indicator of efficiency evaluation is calculated as the ratio between effects and

Table 2
Statistics for the models' estimated coefficients.
Source: Authors' calculation.

Type of econometric model	Correlation coefficient (R-squared)	F-statistic	Probability of F-statistic
Econometric model for the first group of countries	0.9998	25,377.12	0
Econometric model for the second group of countries	0.9993	6113.289	0
Econometric model for the third group of countries	0.9996	10,325.31	0
Regression equation for EU-22 level	0.9947	943.6926	0

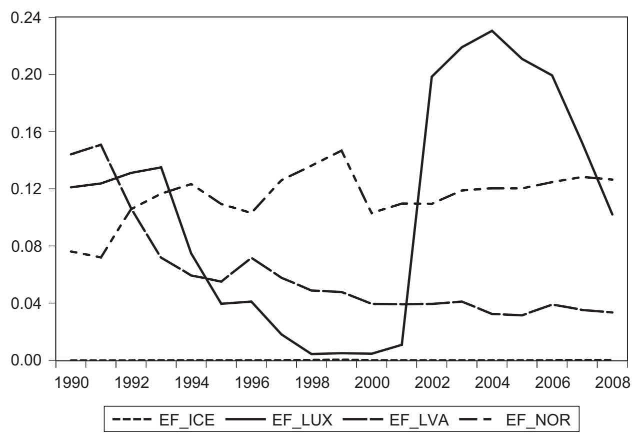

Fig. 1. The evolution of environmental efficiency index.
Source: Authors' calculation.

efforts (expressing the amount of effect per one unit of effort); as a consequence, the value of the indicator should be as big as possible. However, in this case the effect is the emission of CO_2 and our opinion is that this indicator should be as small as possible, which will mean an increased efficiency. Fig. 1 shows the evolution of the index for four suggestive countries Iceland, Latvia, Luxembourg and Norway, as they have the smallest values of the environmental efficiency index.

All four of them are countries with high environmental efficiency, according to Table 1. They are all countries with reduced emissions of CO_2; the small values of the environmental efficiency indices are in most part due to these reduced emissions. It should be observed that Iceland ranks the leading position, for having both high investments in green energy (almost all its energy production and electricity generation is from renewable sources [67]) and reduced CO_2 emissions. It also should be noted that Luxembourg ranks the second leading position not necessarily for having high investments in renewable energy (geographically, there is no question of such resources) but especially for very low CO_2 emissions (Luxembourg has no polluting industries). From 1998 to 2000 it had the smallest values for the environmental efficiency index, thanks to reduced emissions and greater investments in green energy. From 2001, the registered emissions grew, so the environmental efficiency index grew, giving a decreased efficiency.

As a matter of fact, in 2012, three countries presented as an example in the figure above (Latvia, Luxembourg and Norway), are in top five EPI ranking (Environmental Performance Index) [68]. In 2012, Iceland ranks 13 in the EPI ranking, but in 2010 is the top performer thanks to the power obtained from renewable sources and the great control of emissions. This ranking was developed by Yale University, Columbia University in collaboration with the World Economic Forum and the Joint Research Center of the European Commission. "the EPI provides a powerful tool for steering environmental investments, refining policy choices, optimizing the impact of limited financial resources, and understanding the determinants of policy results" [69]. It "focuses on two overarching environmental objectives: reducing environmental stresses to human health and promoting ecosystem vitality and sound natural resource management" [69].

Going further in our analysis, we should look at the obtained econometric models. First of all, the intercepts for each model are expressed as a measure composed of:

- a coefficient representing the deviation from the mean value of intercept for the countries in the group;
- a coefficient representing the mean value of intercept for the countries in the group.

$$\mathrm{Ef\_ROM} = -3.2954 - 1.534 + 0.0348 \times \mathrm{GI\_ROM} + 1689.8231 \times \mathrm{CE\_ROM} + 0.1121 \times \mathrm{EG\_ROM} \quad (35)$$

For instance, for Romania, the intercept is -4.8294, calculated as a sum of deviation from the mean -3.2954 and the mean for the group -1.534. Considering all independent variables being equal with zero, the index of efficiency has the value of the intercept. In all cases, for all countries the intercept is negative, showing that negating the influence of the three mentioned independent variables means having a level of efficiency below 0. These could indicate that there are other factors influencing efficiency that were not included in the study.

The first independent variable, GDP per capita and per unit of renewable investment, has a positive influence over the index, for all states, no matter the group they are part of

$$\mathrm{Ef\_EU} = -7.2027 + 0.004422 \times \mathrm{GI\_EU} + 0.7913 \times \mathrm{CE\_EU} + 3659.1982 \times \mathrm{EG\_EU} \quad (36)$$

For instance, at EU-22 level, if GDP per capita and per unit of renewable investments increases with one unit, the value of the index raises with 0.004422. In the same time, in European Union a positive influence from CO_2 intensity and energy intensity is revealed. So, if the amount of carbon per energy consumed increases with one unit, the efficiency is influenced in the same direction. In our case, this is not a desirable situation, as the efficiency index should have small values in order to indicate high degree efficiency.

The same thing happens in the case of energy consumed to obtain a unit of GDP per capita. There is a logic connection between the independent variable's and the dependent variable's evolution

$$\frac{C}{I} = \frac{G}{I} \times \frac{C}{E} \times \frac{E}{G} \quad (37)$$

If the energy consumption (E from equation (37)) grows, than the carbon emissions (C from equation (37)) will grow too, determining a greater value for the environmental efficiency of green investments index (C/I from equation (37)), which in fact means inefficiency. Only for three countries, namely Turkey, Latvia and Denmark, the estimated coefficients associated to energy intensity, are negative. In other words, if the energy intensity grows with one unit, the efficiency index decreases with the values of estimated coefficients: 0.07903 for Turkey, 4.25186 for Denmark, 0.00127 for Latvia.

All coefficients are correctly estimated, because the probabilities associated to reported t-statistic are zero or small enough, less than the 0.05 level of significance. In Table 2 are presented values for correlation coefficient (which emphasis the power of statistic relation of the dependent variable with the independent variable [71]) and *F* test with its associated probability. The null hypothesis of *F* test is that all slope coefficients (excluding the intercept) are equal to zero. The probability associated to the test is telling us to reject the null hypothesis as it has a value equal with zero, less than 0.05 level of significance. The values of *R* squared are very close to one for each econometric model, no matter the group of countries and even for the EU-22 equation. This indicates that the econometric models explain a high percentage of the dependent variable's variation.

If we are talking about the sensitivity of the model's results, we can specify that there is definitely a sensitivity reported to all specifications used in estimation. As we explained before, the revealed results are significant taking into consideration the application of Ordinary Least Squares method, with cross section specific coefficients, fixed cross section effects and cross section weights.

We will briefly describe the changes in the model's results, implied by applying new specifications. The effective appliance of them could represent a further improvement of the model. Such an update of the model could generate new results that can be used to study its sensitivity to the variety of specifications or to undertake a comparison of results generated by different estimation methods. There is no doubt that an important shift like the one proposed, could make the subject of a further scientific research.

So, to continue with describing the specifications that can support changes, we will first focus on the assumption for regression coefficients. We already explained that "cross section specific coefficients" means obtaining a different coefficient for each variable in each country. We could also choose an assumption that refers to "period specific coefficients". This configuration provides a different coefficient for each observed period, in our case for each year. So, the number of coefficients will equal the number of years multiplied by the number of independent variables. The focus will be on each period's characteristics and not anymore on each country's characteristics.

Moreover, the assumptions concerning the errors were chosen as "cross section fixed effects" and "cross section weights". Regarding the type of effects that can be used, they are either fixed or random, for cross section or period. The choice for "cross-section fixed effects" helped obtaining a unique constant for each country. This constant or intercept counts for unobserved variables that vary across time and remain constant for each country. It is obvious that selecting "period fixed effects" will generate an intercept for each period, in other words an unobserved variable which is constant over time while varying across countries. So, the option for fixed effects describes omitted variables which vary across one dimension of the panel data and stay constant on the other one.

With respect to random effects, things are simpler, as the country specific effects or period specific effects are considered random, not correlated with the independent variables.

In order to allow for a different variance for each country, we used cross section weights; this option assumes the presence of cross-section heteroskedasticity. Another option which includes also a correction for contemporaneous correlation and not only for heteroskedasticity is "cross section SUR". SUR stands for Seemingly Unrelated Regression. There are also the feature of period weights which allows for a different variance for each period (or in other words for period heteroskedasticity) and the feature of "period SUR" analogous to "cross section SUR", but referring to both period heteroskedasticity and correlation of errors across periods within a given cross section.

So, by presenting these specifications, it results a variety of estimation options for computing regression coefficients. It also results two potential ways of changing the perspective of the econometric model. The first one refers to transforming the fixed effects model into a random effects model, with totally different coefficients for variables of interest. The second one obviously reflects the examination of the estimation output from a time perspective, instead of a cross section view.

To conclude, the limitations of this study revolve around the next aspects:

- the methodology used to obtain the Investments in Renewable Energy indicator offers certain values, that can change if another method of calculation is used. This could also influence the final results and the values of estimated coefficients;
- the method of estimation (Ordinary Least Squares method) is the option of the authors. It is the most frequently used method, which corresponds to the problem of finding a line (or curve) that best fits a set of data points [70];
- the period of study 1990–2008 is chosen for the data availability. Enlarging or reducing the period might conduct to obtaining different results.

Therefore, although carefully preparing this research, we are aware of its shortcomings and the need of extended investigation.

6. Conclusions

In studying the efficiency of investments, irrespective of domain, investors were always interested in the economic aspect of the efficiency. Later, when the social aspect gained attention, the social efficiency joined the economic efficiency in establishing the total efficiency of investments projects. As the new sustainable development era governs our existence, we appreciate that another aspect of efficiency should be also analyzed along with these two mentioned before, namely the environmental or the ecological aspect.

This paper aimed to bring into attention a new concept, "the environmental efficiency of investments in renewable energy" and to calculate and study an index associated to this concept. The analysis was conducted for 25 European countries and for the level of European Union, taking into consideration the fact that some of these countries are part of EU. As it was necessary to use efficiency indicators in our analysis, the following were calculated: the environmental efficiency index (efficiency of investments in renewable energy), the energy intensity, the CO_2 intensity, the GDP per capita and per unit of renewable energy investment. All these indicators were included in an econometric model with two dimensions (a spatial one and a temporal one), aspect characteristic to panel data. The source of inspiration for this model was the Kaya identity, an equation relating energy to carbon emissions.

The environmental efficiency of investments index calculated for all countries, indicates a high level of environmental efficiency for those countries with values smaller than the level established for EU-22. The same index shows a low degree of environmental efficiency of investments in green energy for those countries with values exceeding the level established for EU-22. The lowest level of environmental efficiency is obtained for Czech Republic, Germany, Poland and United Kingdom. After applying a method of estimation, the econometric models were obtained. All three independent variables reveal a positive influence on the efficiency index; this is not a good thing to happen if we think on the significance of the index which reflects high level of efficiency if registers small values. For instance, if there are increases in the energy intensity of a country, than the environmental efficiency

index increases with the value of estimated coefficient for energy intensity.

Future research can reveal other important relations and levels of environmental efficiency for investments in renewable energy. As the green energy became the “most wanted” resource of this millennium, we consider that it is absolutely necessarily to study all three aspects regarding the efficiency of investments in renewable energy. Taking into consideration the above presented limitations and the explanation regarding the model's sensitivity, we consider that further ways of improving the model should be reported to them. Moreover, other variables should be included among independent variables. We already included economic (GDP per capita and investments in renewable energy) and environmental variables (CO_2 emissions) or specific to the area of study (energy consumption). It would be of great importance to highlight the influence of labor or technology to environmental efficiency of investments in renewable energy. In this way, the analysis of RE investments' efficiency through econometric methods will become more comprehensive.

Acknowledgments

This work was co-financed from the European Social Fund through Sectoral Operational Program Human Resources Development 2007–2013, project number POSDRU/107/1.5/S/77213 “Ph.D. for a career in interdisciplinary economic research at the European standards”.

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